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RESEARCH MEMORANDUM

AN EXPERIMENTAL INVESTIGATION OF WHEEL SPIN-UP DRAG LOADS

By Benjamin Milwitzky, Dean C. Lindquist,
and Dexter M. Potter

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Langley Field, Va.

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AN EXPERIMENTAL INVESTIGATION OF WHEEL SPIN-UP DRAG LOADS

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SUMMARY

This paper presents some recently obtained information on landing-gear applied drag loads and on the nature of the wheel spin-up phenomenon in landing, based on a program of tests under controlled conditions in the Langley impact basin. In particular, a study has been made of the nature and variation of the coefficient of friction between the tire and the runway during the wheel spin-up process. Also, comparisons have been made of the various results obtained in impacts with forward speed, impacts with forward speed and reverse wheel rotation, spin-up drop tests, and impacts with forward speed and wheel prerotation.

INTRODUCTION

In recent years the problems associated with landing-gear drag loads have assumed increased importance in the design of airplanes. Although drag loads may lead to critical design conditions for such items as the landing gear, drag bracing, parts of the wing, engine mounts and nacelles, tail booms, the afterfuselage, and even tail surfaces, comprehensive reliable information on drag loads is meager and existing data are often in conflict.

The drag-loads problem may be logically resolved into two major aspects, namely, (a) the external applied loads, which are the forces developed between the tire and the runway during the wheel spin-up process in landing, and (b) the dynamic loads induced in the landing gear and various other parts of the airplane structure by the applied loads. The applied ground loads serve as the forcing function which, in conjunction with the mass and flexibility characteristics of the airplane, governs the dynamic response of the structure and, thus, the loads and stresses developed in the airframe.

At the present time a number of dynamic-analysis methods exist which, while not perfect and often laborious, permit reasonable accuracy in the calculation of the dynamic response if the forcing function is known. One of the main problems seems to be: What is the forcing function? This paper is therefore concerned primarily with the applied

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ground loads and the physical phenomena involved in the wheel spin-up process and in particular with the variation of the actual coefficients of friction developed between the tire and the runway. The results to be presented cover four distinct types of impact conditions; namely, impacts with forward speed, impacts with forward speed and reverse wheel rotation, stationary spin-up drop tests, and forward-speed impacts with wheel prerotation.

In the past, attempts to investigate systematically the applied ground loads and the coefficient of friction by correlation of flight-test results have generally been impeded by difficulties introduced by the relatively large amount of scatter normally found in flight-test data as a result of the large number of uncontrolled and generally unmeasured variables involved and, probably most important, by the fact that such data are usually obtained with strain gages mounted somewhere in the landing-gear structure, which give a measure of the local strain or response rather than of the applied ground loads. The results of spin-up drop tests have also been subject to question because of the artificial conditions imposed.

As a result, it was felt that one of the best contributions that the NACA could make in the field of ground loads at this time would be to study the applied drag loads and the wheel spin-up phenomenon under controlled conditions and with instrumentation specifically designed to measure the applied ground loads. The Langley impact basin was chosen for the initial phases of this program and a removable concrete landing strip was installed for the tests. The impact-basin equipment permits a fairly large amount of control in presetting and measuring the impact parameters involved and also permits the use of specialized instrumentation which would be difficult to incorporate in an airplane.

EQUIPMENT AND INSTRUMENTATION

The impact-basin equipment consists primarily of a carriage which is catapulted down a track and which incorporates a dropping mechanism for producing an impact of the landing gear with the runway. Thus, the equipment may be likened to a drop-test tower on wheels. A schematic view of the impact-basin carriage equipped for landing-gear testing is shown in figure 1. The maximum forward speed of the carriage is 60 miles per hour and the maximum dropping weight is 2500 pounds. Wing lift forces are simulated mechanically. The landing gear used in the present investigation is a main-landing-gear unit designed for a T-6 or SNJ trainer airplane having a gross weight of about 5000 pounds. The gear is fitted with a 27-inch smooth-contour (type I) tire having a non-skid tread. The tire inflation pressure is 32 pounds per square inch. In the present tests the gear was inclined forward at 15° with respect to the vertical. All tests were on a concrete surface.

A sketch of the landing-gear installation is shown in figure 2. Of the various types of specialized instrumentation used in the tests, probably the most important is the two-component axle dynamometer which was specially developed for this investigation. This axle dynamometer, which is of the electrical strain-gage type, measured the axial and normal forces transmitted from the axle to the fork of the landing gear, from which the vertical and horizontal forces at the axle can be readily determined. Although the axle-dynamometer measurements do not, in general, differ greatly from the applied ground loads, there is a difference, equal to the inertia reaction of the mass between the dynamometer and the ground. The actual applied ground loads are therefore obtained by adding these inertia forces, which are determined from accelerometer measurements, to the axle-dynamometer measurements. Measurements of the ground loads obtained in this manner check very closely with data obtained simultaneously with a ground dynamometer or reaction platform in stationary spin-up drop tests. (See, for example, fig. 3.)

Also included in these tests was instrumentation to measure the instantaneous skidding velocity of the surface of the tire with respect to the runway. The skidding velocity was obtained from measurements of the axle translational velocity, the wheel angular velocity, and the effective skidding radius of the tire.

A special effort was made to employ high-frequency instrumentation and recording equipment in order to minimize instrument-response errors.

RESULTS AND DISCUSSION

Fundamentals of Wheel Spin-Up Process

Forward-speed tests.- Figure 4 shows several typical time histories of the applied ground loads as measured in impacts with forward speed and illustrates some of the fundamentals of the wheel spin-up process. Data are presented for impacts at a given vertical velocity V_{V_o}, 9.6 feet per second in this case, and at horizontal velocities V_{H_o} of 12, 30, and 57 miles per hour. In the upper graph, the top curves show time histories of the applied vertical load and the bottom curves show the drag load. The lower graph shows the variation of the coefficient of friction during the spin-up process. The coefficient of friction is simply the instantaneous ratio of the applied drag load to the applied vertical load. It should be noted that the friction-coefficient scale does not extend down to zero.

A number of basic effects can be seen from this figure. As the forward speed is increased the time to reach the maximum drag load and the time required for wheel spin-up is increased. During this period

the tire is skidding relative to the runway as the wheel is being accelerated from zero initial rotational velocity up to ground-rolling speed by the drag load. The area under the drag-load—time curve represents an impulse which, acting through the deflected radius of the skidding tire, produces an angular impulse that must equal the change in angular momentum of the wheel during the spin-up process. The higher the initial horizontal velocity, the greater is the required impulse for spin-up, the more the skidding is prolonged, the greater is the vertical load when the wheel comes up to speed, and the greater is the maximum drag load.

As can be seen, the increased drag loads are accompanied by a substantial increase in the vertical load. This increase in the vertical load arises from two sources; namely, (a) increased friction in the shock strut which results from the larger bending moments produced by the inclination of the resultant of the vertical and drag forces with respect to the axis of the shock strut and (b) the component of the drag force along the axis of the shock strut which tends to increase the rate of closure of the strut, with consequent increase in the shock-strut axial force.

The lower graph (fig. 4) shows that the coefficient of skidding friction increases with time during the spin-up process. Since the skidding velocity is greatest at the instant of initial contact and drops to zero at the instant of spin-up, it is evident that the coefficient of friction increases as the skidding velocity decreases. This effect can also be seen by examining the three lower curves at a given instant of time before spin-up. The curve for 57 miles per hour represents the highest skidding velocity and indicates the lowest coefficient of friction. The maximum values of the coefficient of friction, which correspond to very small values of the instantaneous skidding velocity just prior to spin-up, also decrease with increasing forward speed, probably because of the greater temperature of the surface of the tread rubber which results from the greater work done by the skidding friction force. A more detailed discussion of the characteristics of the skidding friction will be presented in a subsequent section.

Forward-speed tests with reverse wheel rotation.- In an attempt to extend the range of the investigation beyond the 60 miles per hour maximum speed of the carriage, forward-speed tests were made with reverse wheel rotation. The carriage was propelled at its maximum speed and the landing wheel was rotated backward to simulate horizontal velocities at initial contact up to 186 miles per hour.

Figure 5 shows results of two typical tests near the extremes of the horizontal-velocity range obtained in this phase of the investigation. The solid curves are for an initial relative horizontal velocity V_{REL} of 76 miles per hour, whereas the dashed curves are for 186 miles per hour. The vertical velocity in these tests was 7.5 feet per second.

The results for 76 miles per hour are similar in character to those previously discussed. The high-speed results, however, are markedly different. First of all, the time to spin-up is greatly increased, as might be expected, and the wheel does not come up to speed until very much after the maximum vertical load is reached. The drag load throughout the time history, as well as the maximum drag load, is considerably reduced. Similarly the maximum vertical load is much less, because of the reduced friction in the shock strut, which results from the fact that the resultant ground force is more nearly alined with the axis of the shock strut.

The cause of the smaller loads at high speed is the much lower coefficient of friction throughout most of the time history, which results from the higher skidding velocity and the increased heating of the tire surface. In the later stages of the spin-up process, however, the coefficient of friction increases as the skidding velocity decreases, just as in the previous cases. Since the vertical load is fairly small at the instant of spin-up, the maximum drag load is likewise low.

An interesting phenomenon in the case of the high-speed impact is the sudden reduction in the slope of the drag-load—time curve shortly after contact and the marked dropoff in the coefficient of friction. Apparently, at this point the critical temperature of the tread rubber is exceeded because of the very high skidding velocity, and the area of the tire in contact with the runway becomes molten. This situation appears to be only temporary and ceases to exist as the skidding velocity decreases.

Comparison of Maximum Loads in Various Types of Tests

Forward-speed tests and forward-speed tests with reverse wheel rotation.- Figure 6 shows the maximum vertical and the maximum drag loads obtained in the ordinary forward-speed tests and in the forward-speed tests with reverse wheel rotation plotted against the relative horizontal velocity at initial contact. All tests are for a vertical velocity at contact of 7.5 feet per second. The solid circles and the solid-line curves are data from the forward-speed tests below 60 miles per hour; the open squares and the long-dash curves are data from the forward-speed tests at the maximum carriage velocity with reverse wheel rotation.

In order to check on the validity of the reverse-rotation technique, the carriage was also propelled at low speeds and the landing wheel was spun up backward to simulate the original forward-speed tests between 30 and 60 miles per hour. These overlapping tests are shown by the open diamonds and triangles for carriage velocities of 33 and 14 miles per hour, respectively. There appear to be some secondary effects of carriage speed, but in this low-speed region such effects would be expected

to be small. Present indications are that reduced carriage speeds result in smaller loads for a given relative horizontal velocity. This result arises from the fact that reverse-rotation tests do not duplicate the ratio of the skidding velocity to the forward speed of the carriage, called the slip ratio. The effects of slip ratio will be discussed in more detail later. Because of the difference in slip ratio, the actual loads in a true forward-speed test should be somewhat larger than are indicated by the data from the forward-speed tests with reverse rotation. The exact amount of this difference cannot be determined at the present time since there is no way of obtaining actual forward-speed data above 60 miles per hour in the impact basin.

As can be seen from figure 6, the maximum drag load reached a maximum at about 80 miles per hour. At this horizontal velocity the instant of spin-up coincides in time with the occurrence of the maximum vertical load, as can be seen from figure 5. Above this speed, because of the reduced coefficient of friction, the maximum drag load decreased with increasing forward speed, as previously indicated by the time histories. The vertical load increased markedly with increasing drag load, because of shock-strut friction, then dropped as the drag load decreased at the higher horizontal velocities, also as previously noted. The dip in the curve of maximum vertical load at a horizontal velocity of about 20 miles per hour corresponds to the condition of minimum friction in the shock strut. At speeds below 20 miles per hour the resultant force tends to deflect the gear forward; at speeds above 20 miles per hour the resultant force tends to deflect the gear rearward. At about 20 miles per hour the average resultant force is most nearly alined with the axis of the strut, and the bending moment, and thus the strut friction, reaches a minimum, with consequent reduction in the vertical load.

Spin-up drop tests.- In figure 7 the maximum vertical and maximum drag loads obtained in spin-up drop tests are compared with the results of the forward-speed tests previously discussed. In these drop tests the carriage was stationary and the landing wheel was spun up backward before the impact to simulate the effect of forward speed. The vertical velocity at contact in these tests was also 7.5 feet per second. The open circles and short-dash curves show the drop-test data; the solid-line and long-dash curves represent the forward-speed results and are the same as the curves of figure 6.

As can be seen, the spin-up drop tests were in fairly good agreement with the forward-speed tests at the low relative horizontal velocities, the drop tests yielding slightly higher drag loads. At speeds above about 40 miles per hour, however, the drop tests yielded considerably smaller drag loads and smaller vertical loads than did the forward-speed tests, the latter result again indicating the effects of strut

friction. These reductions in load are due primarily to the much smaller coefficients of skidding friction in the spin-up drop tests than in the forward-speed tests throughout most of the horizontal-velocity range, which result from the rubbing of the tire in one spot on the concrete in the case of the drop tests. A better understanding of the nature of the coefficient of friction can be obtained from the following discussion.

Variation of Coefficient of Friction

Figure 8 shows the variation of the coefficient of skidding friction during impact for the three types of tests previously discussed, namely, the impacts with forward speed below 60 miles per hour, the impacts with forward speed and reverse wheel rotation, and the spin-up drop tests. In this figure the coefficient of friction is plotted against the instantaneous skidding velocity of the tire with respect to the runway. Each curve shows the variation of the coefficient of friction during a particular test run. For the sake of clarity, results are shown from only three runs for each type of test. The highest skidding velocity shown for any particular test run (the right-hand extremities of the curves) corresponds to the relative horizontal velocity at the instant of initial contact, which is indicated by the numbers next to each curve. When the skidding velocity reaches zero the spin-up process is finally completed. Thus the course of the impact appears in this figure from right to left. The actual data points for any given run exhibited very little scatter and relatively smooth curves could therefore be drawn through the points with almost no fairing. It should be again noted that the friction-coefficient scale does not extend down to zero.

Let us first examine the results of the forward-speed tests. The main point to be made here is that the coefficient of friction decreases with increasing skidding velocity, from almost 0.9 at 5 miles per hour to about 0.7 at 50 miles per hour.

In the case of the forward-speed tests with reverse wheel rotation, at the low skidding velocities there is general agreement with the true forward-speed data. There is also the general trend of a decreasing coefficient of friction with increasing skidding velocity. This decreasing trend is evident throughout the entire skidding-velocity range and indicates coefficients of friction as low as 0.3 at skidding velocities of 150 miles per hour. It should be noted, however, that, even in the case of impacts at high initial relative velocities, the coefficient of friction reaches fairly high values as the skidding velocity is reduced in the later stages of the spin-up process.

It can be seen that in the early stages of each impact the curves depart from the general trend and the initial values of the coefficient of friction are fairly high. For example, the data from the test at an initial horizontal velocity of 118 miles per hour start out at a coefficient of friction of about 0.6 and rapidly drop to the general trend.

This short-duration effect is believed to represent a transitional stage from an initially cold rubber surface to a more-or-less equilibrium condition represented by the general trend. In other words, for the cold tire the variation of the coefficient of friction with skidding velocity appears to follow a limiting curve through the upper initial points; whereas, for the operating-equilibrium condition the variation is represented by the lower trend, as is diagrammatically illustrated in figure 9. Both trends indicate a decrease in coefficient of friction with increasing skidding velocity, the rate of decrease being more pronounced for the curve labeled "hot."

In the case of the extremely high initial relative velocity of 186 miles per hour (fig. 8), the apparent temporary liquefaction of the tread rubber shortly after initial contact, because of the very high skidding velocity in this region, is manifested by the local drop in the friction coefficient. This effect was previously discussed in connection with the time histories shown in figure 5.

The equilibrium trend for the forward-speed tests with reverse rotation shows a more rapid decrease in the coefficient of friction with skidding velocity than is indicated by the forward-speed tests below 60 miles per hour. This result is apparently due to the effects of slip ratio, which was previously defined as the ratio of the skidding velocity to the forward speed of the wheel. Reverse-rotation tests have higher slip ratios than true forward-speed tests. As a result there is less fresh runway brought into contact with the tire per unit time than in a true forward-speed test, and therefore less cooling effect and a greater tendency for contamination of the runway in the tire contact area by abraded or molten rubber, with a consequent reduction in the coefficient of friction.

The effect of slip ratio is even more marked in the spin-up drop tests. For low initial relative horizontal velocities, the coefficients of friction are generally of the same order as in the forward-speed tests. At these low skidding velocities heating and runway contamination are negligible, even though the tire is always rubbing in one spot on the concrete. At the higher initial relative velocities, however, the tire surface rapidly becomes soft and even molten, and the concrete becomes loaded with gummy rubber which acts as a lubricant. As a result, the transition from a cold tire surface to a hot tire surface is very rapid, and the coefficient of friction becomes very small throughout practically the entire spin-up process. It can be seen that the higher the initial relative velocity, the smaller is the coefficient of friction. For example, at an initial relative horizontal velocity of 155 miles per hour, the average coefficient of friction is less than 0.4. These unrealistically low coefficients of friction in spin-up drop tests indicate why some manufacturers have had to resort to special artificial

reaction-platform surfaces in order to realize coefficients of friction more compatible with experience and with design requirements.

Effects of Prerotation

The last subject to be considered deals with the effects of wheel prerotation in reducing drag loads. It appears that one of the main reasons that prerotation has not come into wider use stems from a general belief that the reductions in drag load would be very small unless the prerotation speed is matched almost exactly with the ground-rolling speed, a requirement which may be rather difficult to achieve in practice.

Figure 10 shows how prerotation affects the drag load. The upper curves are time histories of the vertical load; the lower curves are drag-load time histories. Results are shown for three prerotation speeds ranging from no prerotation to 93 percent or almost complete prerotation. These tests were made at a vertical velocity of 9.6 feet per second and a carriage horizontal velocity of 57 miles per hour. These results show that wheel prerotation permits a major reduction in drag load as well as an accompanying reduction in vertical load.

In order to show more clearly the effect of prerotation on the maximum drag load, figure 11 presents a graph of the ratio of the maximum drag load with prerotation to the maximum drag load without prerotation, as a function of the percent prerotation. These results are also for a carriage horizontal velocity of 57 miles per hour and a range of vertical velocities. The data for the high vertical velocities representative of design sinking speeds indicate substantial reductions in maximum drag load, even for partial prerotation. For example, 50 percent prerotation reduced the drag load by almost 40 percent in these tests. At the lowest vertical velocity, however, partial prerotation, while still beneficial, does not permit as marked a reduction in drag load.

The foregoing results correspond very closely with what would be predicted from curves of maximum drag load against initial relative horizontal velocity, such as previously shown in figure 6.

In evaluating these prerotation results, a word of caution is necessary. In the prerotation tests discussed here the carriage horizontal velocity was 57 miles per hour. As can be seen from figure 6 this velocity is below the forward speed at which the hump in the maximum drag-load curve occurs. At speeds below the hump, reducing the relative velocity by prerotation, even partial prerotation, always serves to

reduce the drag load. For horizontal velocities above the hump, however, partial prerotation could very well produce an increase in drag load if the relative velocity were reduced to values in the vicinity of the hump. This possibility should always be considered in the design of prerotation devices and care taken to insure that the relative velocity produced by prerotation is well below the hump velocity. This restriction still provides a great deal of latitude in matching the forward speed and does not violate the previous conclusion that appreciable reductions in drag load can be obtained even with incomplete prerotation. It would also appear that prerotation should be advantageous from the standpoint of fatigue, because of the reduction of the fore-and-aft oscillatory loading (so-called spin-up and spring-back loads) dynamically induced by the drag load.

SUMMARY OF RESULTS

This paper has presented some recently obtained information on landing-gear applied drag loads and on the nature of the wheel spin-up phenomenon in landing. These results are based on a program of tests under controlled conditions, which is still in progress in the Langley impact basin. In particular, a study has been made of the nature and variation of the coefficient of friction between the tire and the runway during the spin-up process. Also, comparisons have been made of the various results obtained in impacts with forward speed, impacts with forward speed and reverse wheel rotation, spin-up drop tests, and impacts with forward speed and wheel prerotation. A summary of the major findings follows:

1. The maximum applied drag load increases with increasing initial horizontal velocity, reaches a maximum value at the horizontal velocity at which wheel spin-up coincides in time with the occurrence of the maximum vertical load, then decreases as the horizontal velocity is further increased, primarily because of a reduction in the coefficient of friction with increasing skidding velocity.

2. The vertical load increases substantially with increasing drag load, because of increased friction in the shock strut which results from the bending moments produced by the inclination of the resultant ground force with respect to the axis of the shock strut.

3. Because of differences in slip ratio, forward-speed impacts with reverse wheel rotation give somewhat smaller loads at the higher relative horizontal velocities than true forward-speed impacts; the higher the forward speed in the reverse rotation impacts, of course, the smaller is the difference in load.

4. At horizontal velocities representative of actual airplanes, stationary spin-up drop tests give considerably smaller drag and vertical loads than impacts with forward speed.

5. The coefficient of friction between the tire and runway decreases appreciably with increasing skidding velocity. During an impact there is a transition from an initially cold tire surface to a more-or-less equilibrium condition; consequently the coefficient of friction starts out at fairly high values representative of the cold tire and rapidly drops to values corresponding to the equilibrium condition. Both trends indicate a decrease in coefficient of friction with increasing skidding velocity. It should be noted, however, that even in the case of impacts at high initial relative velocities, the coefficient of friction reaches fairly high values as the skidding velocity is reduced in the later stages of the spin-up process.

6. The variation of the coefficient of friction with skidding velocity is also dependent on the slip ratio. The importance of slip ratio is particularly marked in the case of spin-up drop tests. For low relative velocities the coefficients of friction in drop tests are approximately the same as in forward-speed tests. At higher relative velocities, however, the coefficient of friction drops to very small values as a result of the effects of heating and lubrication of the contact area by abraded or molten rubber.

7. Wheel prerotation, even partial prerotation, appears to be very effective in reducing drag loads. Care should be taken, however, to insure that the relative velocity produced by prerotation is well below the velocity at which the drag-load hump occurs; otherwise the drag load may be increased rather than reduced. This restriction still permits considerable latitude in matching the forward speed and does not violate the conclusion that prerotation can greatly reduce the maximum drag load.

As has been previously mentioned, the results of the present investigation were obtained with a small landing gear equipped with a relatively low-pressure tire. Just how general these results are is as yet unknown. In particular, similar data are needed to determine the effects of wheel size, tire pressure, vertical load, rate of change of vertical load, slip ratio, heating produced by the skidding energy absorbed by the tire, different runway surfaces and materials, and other factors which may influence the coefficient of friction.

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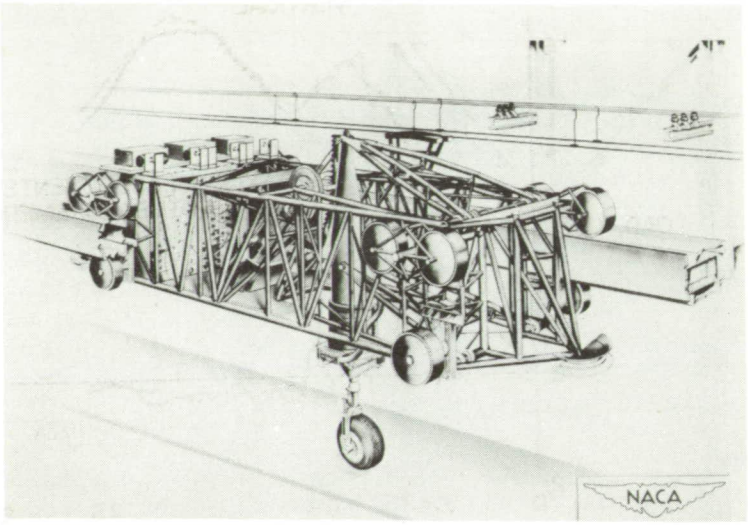


Figure 1.- View of impact-basin carriage and landing-gear test specim

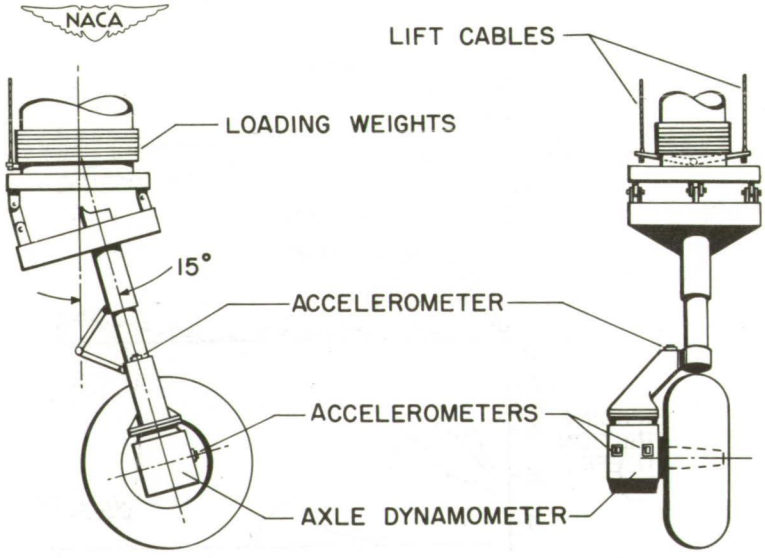


Figure 2.- Sketch of landing gear and load-measuring instrumentation.

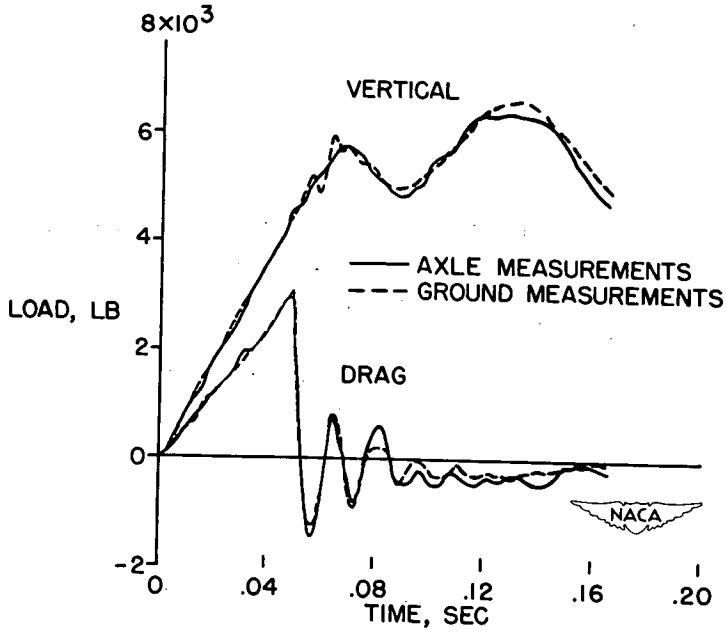


Figure 3.- Comparison of loads measured with axle dynamometer and ground dynamometer, including inertia-load corrections, in spin-up drop test.

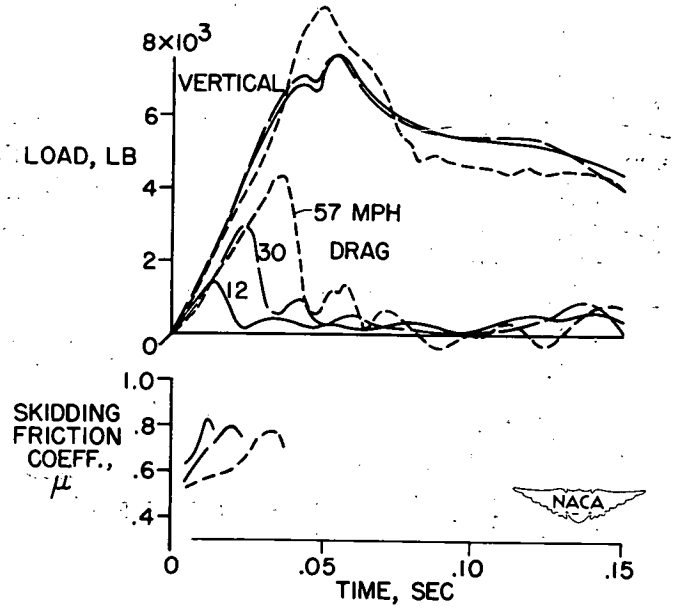


Figure 4.- Time histories of drag load, vertical load, and coefficient of skidding friction in impacts with forward speed. V_{V_o} = 9.6 fps.

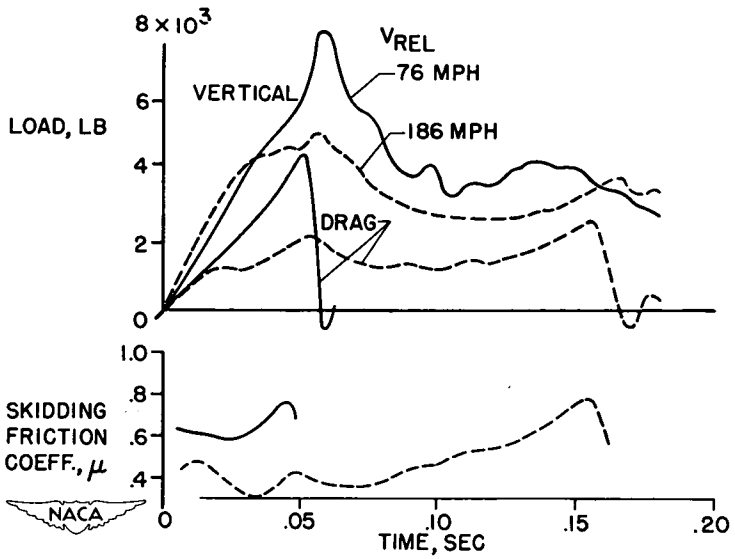


Figure 5.- Time histories of drag load, vertical load, and coefficient of skidding friction in impacts with forward speed and reverse wheel rotation. V_{V_o} = 7.5 fps; $V_{carriage}$ = 57 mph.

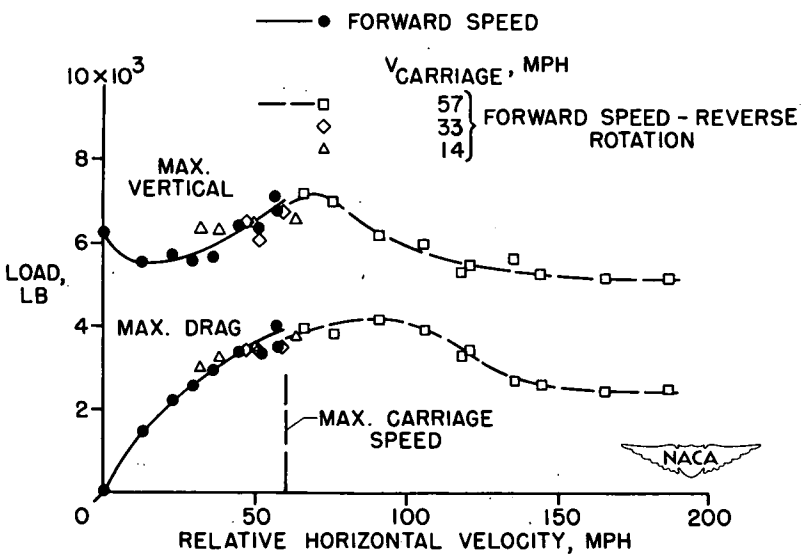


Figure 6.- Maximum drag and vertical loads in impacts with forward speed and in impacts with forward speed and reverse wheel rotation. V_{V_o} = 7.5 fps.

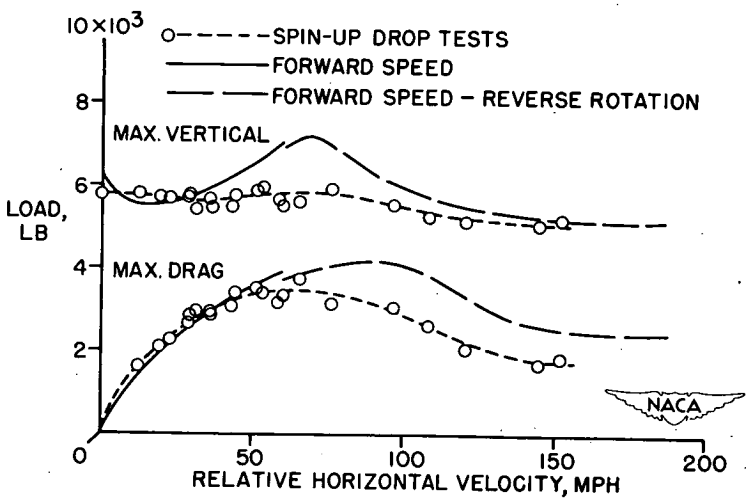


Figure 7.- Comparison of maximum drag and vertical loads in spin-up drop tests with results of forward-speed impacts with and without reverse wheel rotation. V_{V_o} = 7.5 fps.

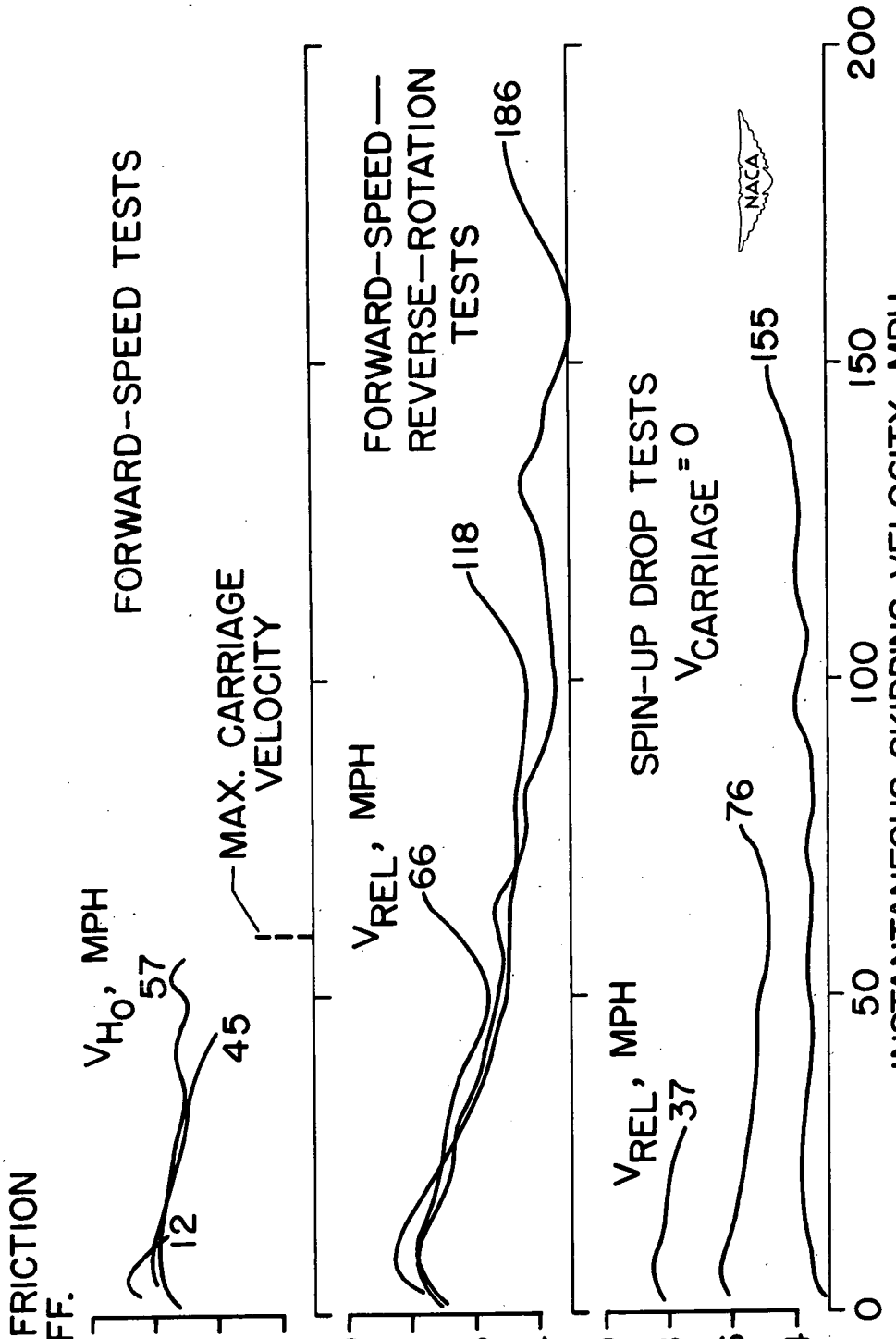


Figure 8.- Variation of coefficient of skidding friction with skidding velocity in impacts with forward speed, impacts with forward speed and reverse wheel rotation, and spin-up drop tests.

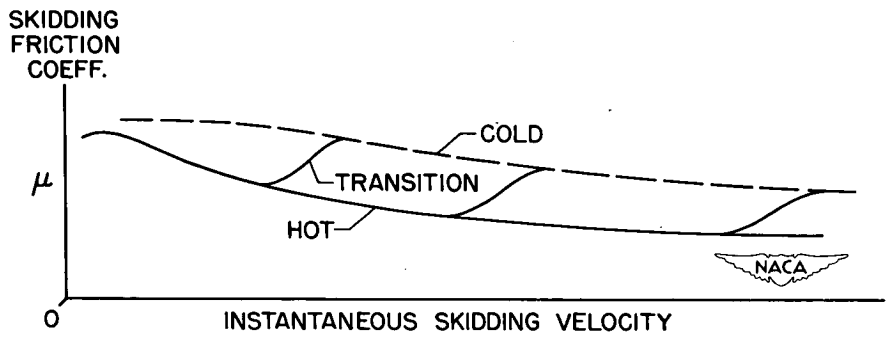


Figure 9.- Diagrammatic representation of variation of coefficient of skidding friction.

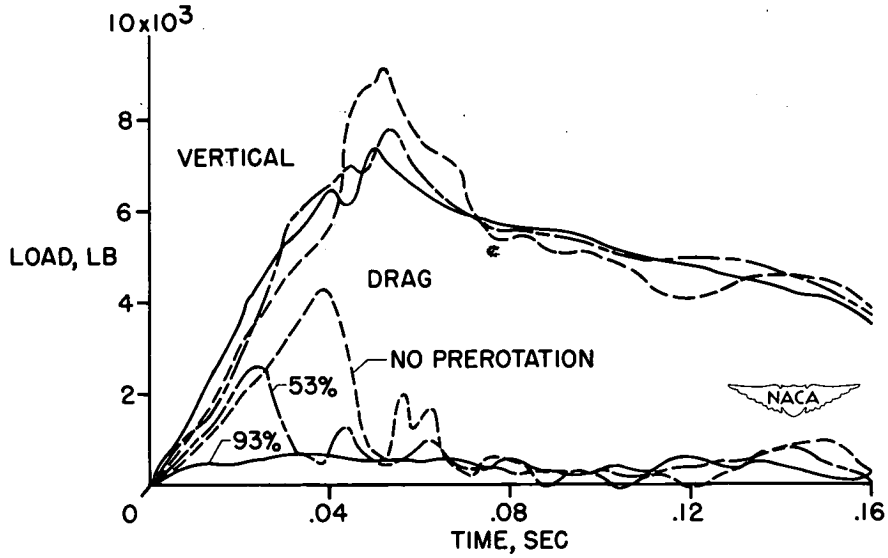


Figure 10.- Effect of wheel prerotation on time histories of drag and vertical loads. V_{V_o} = 9.6 fps; $V_{carriage}$ = 57 mph.

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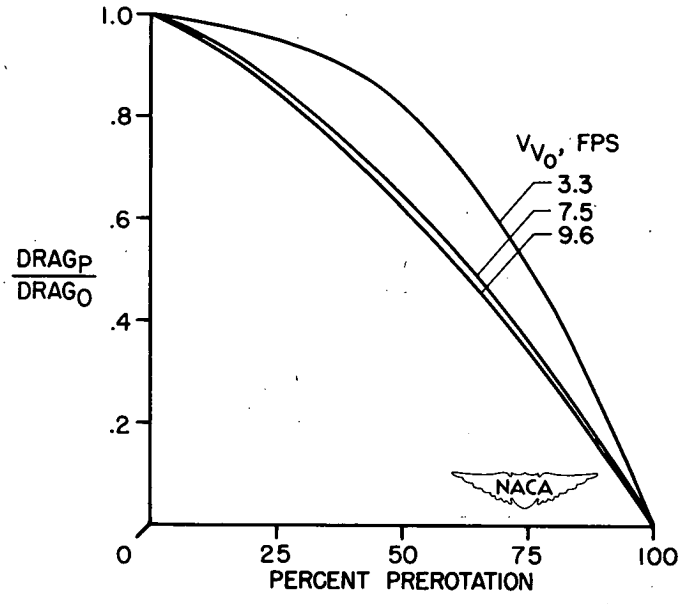


Figure 11.- Effect of wheel prerotation on maximum drag loads in impacts with forward speed. $V_{carriage}$ = 57 mph.

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